SEISMIC CALIBRATION OF THE EUROPEAN ARCTIC

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ABSTRACT

The purpose of this two-year effort, which started on 1 January 1999, is to support the construction of the U.S. Department of Energy (DOE) Comprehensive Nuclear-Test-Ban Treaty Knowledge Base for detecting, locating and identifying seismic events in the area of northern Fennoscandia, the Kola Peninsula, Novaya Zemlya, and the surrounding waters of the Barents and Kara Seas. The main objectives of the effort are to assemble a set of historical seismic observations suitable for characterizing all aspects of seismic wave propagation and seismic sources in this region, to describe the principal seismic phases observed in the seismograms, and to calibrate the region with respect to seismic wave propagation (travel-times and amplitude-distance relations).

The main emphasis of work on this contract so far has been on data collection. Waveform data have been complied for a range of sources in the European Arctic: Nuclear tests at the Novaya Zemlya test site, peaceful nuclear explosions conducted in the area, earthquakes and presumed underwater explosions from 1970 to the present, and representative blasts from mining operations in the Kola Peninsula, northern Norway, Sweden, Finland and adjacent regions of European Russia. Waveform data collected under this effort have been provided in CSS 3.0 format, with the appropriate metadata included, to DOE through the Lawrence Livermore National Laboratory, to the U.S. Department of Defense through the Center for Monitoring Research, and to the U.S. National Data Center. So far, segmented data for 111 events have been extracted and copied to eight CD ROMs. In addition, a set of seven Exabyte tapes has been produced, containing continuous data in the form of 15-day segments around the origin times of three events that occurred in the Noyaya Zemlya region during 1995-1997. Additional data for events of special interest will be delivered during the year 2000.

The project is a collaborative effort between NORSAR and the Kola Regional Seismological Centre (KRSC) of the Russian Academy of Sciences. The main source of data for this project is the historical waveform archives at NORSAR, containing data from the NORSAR teleseismic array and the network of northern European small-aperture arrays. These data have been supplemented with data provided by KRSC for stations AMD and APA in northwestern Russia.

The work under this contract also includes analysis of the data compiled. So far, a study of the P/S ratio as a regional discriminant in the European Arctic has been conducted. Our conclusion from this study is that the P/S ratio, even at high frequencies is, with present knowledge, not sufficiently stable to be used as a reliable discriminant between earthquakes and explosions. Future application of this discriminant will require extensive regional calibration and detailed station-source corrections. Work continues on other aspects of data analysis, such as a determination of bounds on seismicity in the Kara Sea.

Key Words: data collection, characterization of seismic phases, seismic calibration

OBJECTIVE

This purpose of this research is to support the construction of the DOE CTBT Knowledge Base for detecting, locating and identifying seismic events in the area of northern Fennoscandia, the Kola Peninsula, Novaya

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Zemlya, and the surrounding waters of the Barents and Kara Seas. This is done by assembling a set of historical seismic observations suitable for characterizing all aspects of seismic wave propagation and seismic sources in this region, by describing the principal seismic phases observed in the seismograms, and by calibrating the region with respect to seismic wave propagation.

RESEARCH ACCOMPLISHED

Collection and delivery of waveform data

An important aspect of this project is the compilation of a data base of events to be used for calibration purposes. In fulfillment of this goal, waveform data have now been collected for a range of sources in the European Arctic: Nuclear tests at the Novaya Zemlya test site, peaceful nuclear explosions conducted in the area, earthquakes and presumed underwater explosions, and representative blasts from mining operations in the Kola Peninsula, northern Norway, Sweden, Finland, and adjacent regions of European Russia. The basis for the selection of events for inclusion in this data base has been regional and other bulletins covering this area. The bulletin sources have thus included the bulletin of the International Seismological Centre (ISC), the bulletin of the NEIC (USA), the IDC Reviewed Event Bulletin, the NORSAR regional and teleseismic bulletins, and the bulletin of the Kola Regional Seismological Centre.

Table 1 gives an overview of the available digital stations that have formed the primary data source for this project. The table specifies the station type (array, 3C), the station location, the operating organization, and the years during which each station has been in operation. Note that some data from the Hagfors array in Sweden and the GERESS array in Germany have also been included in the data base.

Station	Station Type	Station Location	Operating Organization	Data Availability (in NORSAR's archives)
NORSAR large-aperture array	Array	60.82°N 10.83°E	NORSAR	1971-present
NORESS array	Array	60.73°N 11.54°E	NORSAR	1984-present
ARCESS array	Array	69.53°N 25.51°E	NORSAR	1987-present
Spitsbergen array	Array	78.18°N 16.37°E	NORSAR	1992-present
FINESS array	Array	61.44°N 26.08°E	Univ. of Helsinki	1990-present
Apatity array	Array	67.61°N 32.99°E	KRSC	1992-present
Amderma array	Array, 3C	69.74°N 61.66°E	KRSC	1994-present

Table 1. This table gives an overview of available digital stations that form the primary data source for this project.

The waveform data compiled have been copied to a set of 8 CD-ROMs. CD-ROM No. 1 in this set contains data from 30 underground nuclear test explosions conducted at Novaya Zemlya during 1971-1990 and recorded on the large-aperture NORSAR seismic array. This collection covers all nuclear test explosions on Novaya Zemlya during this time interval, except the m_b 5.7 explosion on 27 September 1978, as the NORSAR array data acquisition system was out of operation on this date. Data recorded at the NORSAR array for a one kiloton chemical explosion conducted on Novaya Zemlya in 1987 are also included. The ray paths from the two Novaya Zemlya test sites to the NORSAR large-aperture array are shown in Fig. 1.

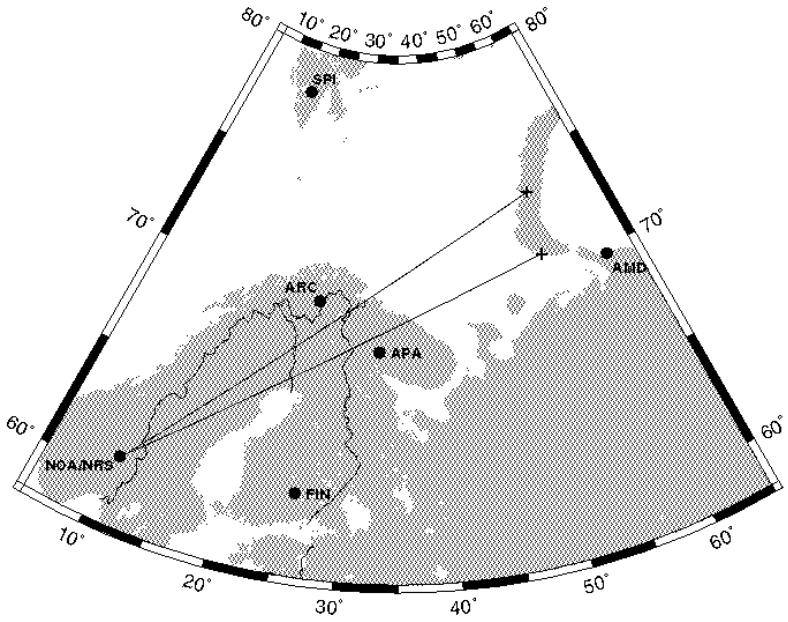

Fig. 1. Ray paths for the Novaya Zemlya events compiled in CD-ROM No. 1.

The data on CD-ROMs Nos. 2-8 comprise all available recordings from 84 seismic events, as collected from the following stations and arrays: Amderma, Apatity, ARCES, FINES, GERES, Hagfors, NORSAR, NORES and SPITS. The data cover the time interval from 1979 through 1998, and have magnitudes ranging from 2.3 to 5.9. These events are shown in Fig. 2.

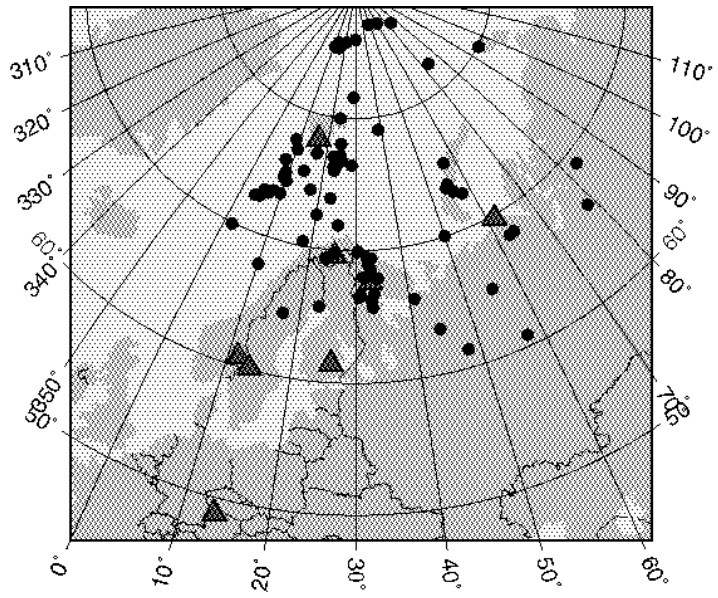

Fig. 2. The map shows the epicenters for the 84 events (filled circles) contained on CD-ROMs Nos. 2-8. The stations for which waveforms are collected are shown as triangles.

An example of the data in this data set is provided in Fig. 3., which shows the NORSAR array recordings from an underwater chemical explosion of 8 tons, set off in the sea at 71.90°N, 25.79°E, and conducted as part of the FENNOLORA deep seismic sounding experiment in 1979.

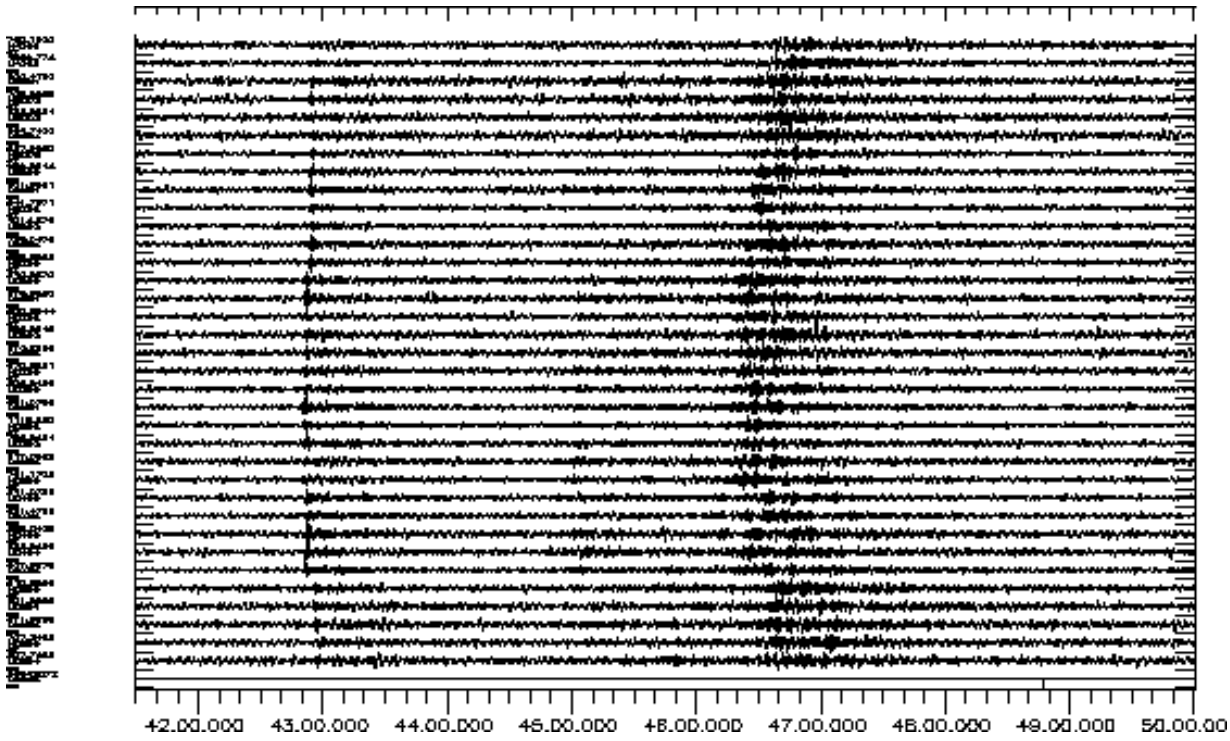

Fig. 3. Data example from the August 17, 1979, event recorded on the 42 short-period channels of the NORSAR array. The source was an underwater chemical explosion of 8 tons, conducted as part of the FENNOLORA deep seismic sounding experiment.

In accordance with the contract, the set of CD-ROMs as described above has been distributed to the US Department of Energy through the Lawrence Livermore National Laboratory, to the US Department of Defense through the Center for Monitoring Research, and to the US National Data Center. All data are in the CSS3.0 format, and appropriate metadata have been provided in accordance with the specifications given by Carr et al (1998). In addition to the segmented data described above, some sample continuous data segnments of lengths up to 15 days have been retrieved from the data archives and provided to the DOE.

P/S ratio as a regional discriminant in the European Arctic

We have used data from seismic stations operated by NORSAR, the Kola Regional Seismological Centre (KRSC) and IRIS to study the characteristics of regional phases in the European Arctic, with emphasis on the P/S ratio discriminant. In particular, we study the variability of the P/S ratio as a function of frequency across various regional arrays. Previous studies using the large-aperture array NORSAR have shown a large variability in P/S ratios for sensors in the array when analyzing a given seismic event. This variability is most pronounced at low frequencies (1-2 Hz), but significant even in the higher frequency range.

It is of interest to investigate this variability across smaller arrays, and we have carried out such studies for mining explosions as well as confirmed earthquakes. The variability of the P/S ratio turns out to be very

significant, even across a small array such as ARCES (diameter 3 km). The main source of this variability comes from the P-wave. Although the standard deviation of the P/S ratio across the arrays is less at higher frequencies, it is still large enough to cause concerns for the effectiveness of P/S as a seismic discriminant in this region. We find that using 3-component data (there are four 3-component stations within the ARCES array), the scatter in P/S ratios is somewhat smaller than when using vertical components alone. However, some caution should be exercised in interpreting this result because of the low number of 3-component sensors.

When assessing data from a regional network for the same event, we find that the P/S amplitude ratio shows large variability for the same source type and similar propagation paths. This effect is most pronounced at relatively low frequencies, but it is also significant at higher frequencies. Our conclusion from this study is that the P/S ratio, even at high frequencies, is with current knowledge not sufficiently stable to be used as a reliable discriminant between earthquakes and explosions. Future application of this discriminant will require extensive regional calibration and detailed station-source corrections.

We have also calculated spectrograms for a set of seismic events of various source types. The most interesting feature observed in the clear evidence of spectral scalloping for an underwater explosion near Murmansk recorded at the ARCES array at a distance of about 300 km. Such spectrograms might contribute useful information in interpreting future seismic events in the region.

Ground truth events

As a separate effort under this contract, waveform data were collected for nine events that occurred in the northern Norway/Kola peninsula region during the interval May-August 1999. These events are well-located earthquakes and mining explosions, and have been classified in accordance with the "Ground Truth" terminology used for the Calibration Database at the Prototype International Data Center (Bondar and North, 1999). The nine events in this database fall within the categories GT1 (three mining explosions), GT2 (two mining explosions), GT5 (3 earthquakes at Revda in the Kola Peninsula) and GT7 (one earthquake at Masi in northern Norway). For these events, waveform data are available from five permanent stations in this area, as well as from the so-called MASI network comprised of 13 broadband stations temporarily deployed in the county of Finnmark, northern Norway, during May-September 1999. These data have been made available on a CD-ROM that has been distributed as described above for previous data deliveries on this project.

Two events in this database of nine ground truth events have been studied in some detail. The locations of these two events are shown in Fig. 4, which also shows the 13 stations of the MASI network.

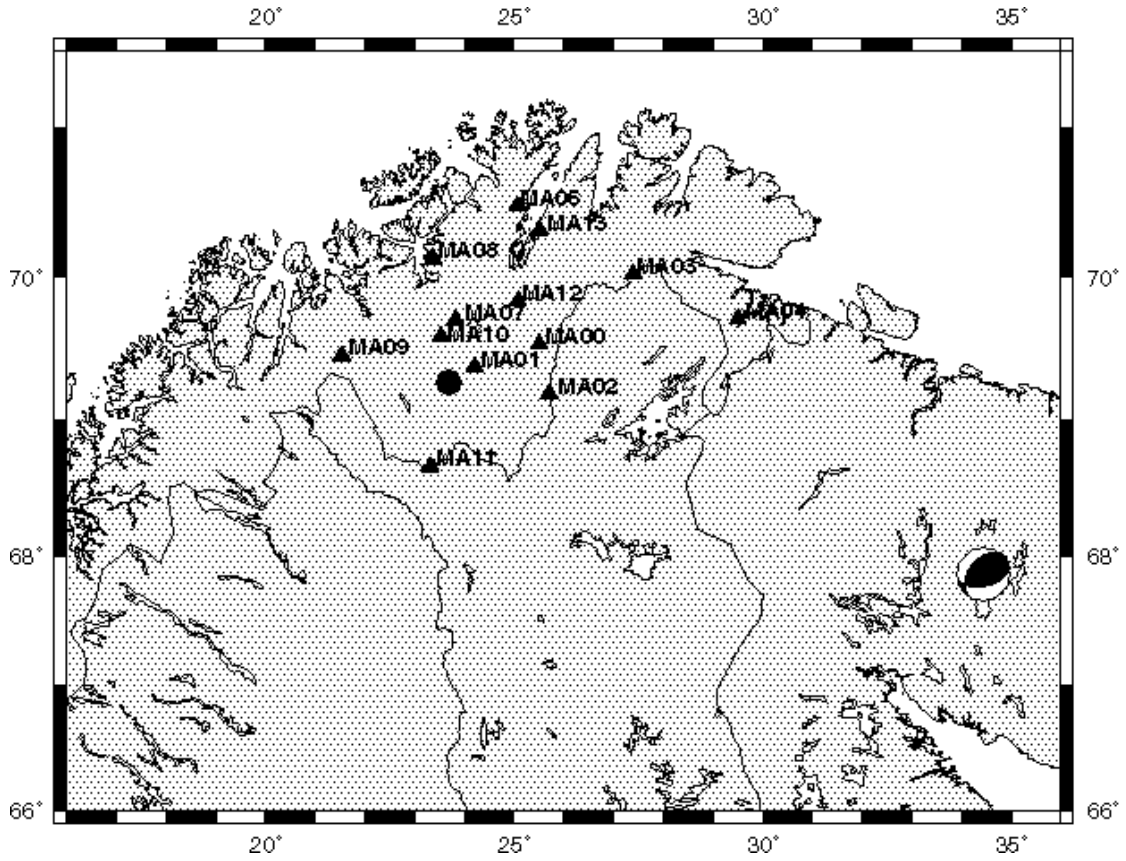

Fig. 4. Map of the 13 MASI stations (triangles) temporarily deployed in Finnmark, northern Norway, during May-September 1999. The dot and the focal plane solution show the positions of the two earthquakes analyzed here (Masi, 22 August 1999, within the MASI network, and Revda, 17 August 1999, in the Kola Peninsula to the east, respectively).

Analysis of the displacement spectra of the MASI network recordings of the 22 August 1999 M_L 2.7 Masi earthquake that occurred within the MASI network, resulted in a relatively high Q of about 1500 in the frequency range 1-10 Hz. The recordings from the Masi earthquake also provided the basis for inferring individual station soil responses (some of the stations of the MASI network were sited on top of thin layers of moraines, whereas others were deployed on solid rock). These results derived from the Masi earthquake records were used to obtain the source spectrum of the Revda M_L 3.9 (M_s 4.2) earthquake of 17 August 1999. The MASI network recordings of this earthquake are shown in Fig. 5. Note that the traces are time-adjusted to align the Rg phases across the network, so that the first Pn onset is outside the frame for the more distantly located stations (at the bottom of the figure).

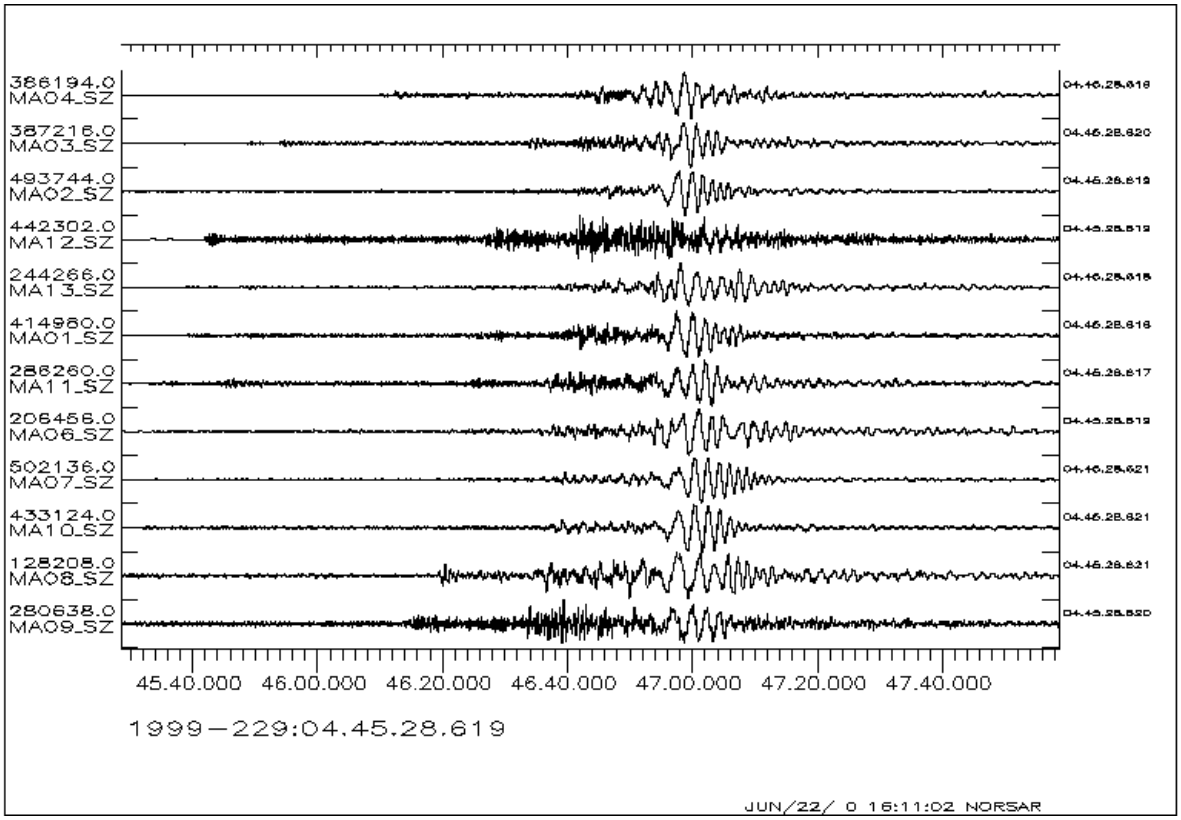

Fig. 5. MASI network recordings of the 17 August 1999 Revda earthquake. The reduction velocity applied is 3.2 km/s in order to align the Rg phase.

The observed spectra for the Revda earthquake can be matched reasonably well with synthetics computed for a circular fault plane of radius 1.6 km, a complete stress drop of 50 bar and a seismic moment of M = 6.7e+22 dyn-cm. The source depth of this earthquake was investigated using a full waveform modelling approach, and the main target in this modelling was the dispersive Rg waves clearly seen in Fig. 5. Matching of synthetic and observed waveforms indicates that the source depth for this event is between 4 and 6 km.

CONCLUSIONS AND RECOMMENDATIONS

Efforts under this contract have resulted in the production of nineCD-ROMs containing data for more than 100 events in the European Arctic, as recorded on arrays and 3-component stations in northern Europe. These data, along with selected continuous data (with data intervals of length up to 15 days), have been made available to the research community. We are in the process of carefully analyzing the events provided in this database in order to ascertain that the events are indeed located within the accuracy estimates given by the various agencies. Our findings in this regard will be provided in future revisions to the database.

The effort also includes some analysis of the data collected. So far, this analysis has focused on the following topics, with results as reported in this paper:

- Study of the P-to-S amplitude ratio as a possible regional discriminant in the European Arctic
- Spetrogram analysis of selected presumed underwater explosions and mining explosions at the Kola Peninsula to identify distinguishing characteristics of these events
- Special analysis for a few events with ground truth information using a comprehensive collection of waveform data to include an extended set of stations in the Fennoscandian-northwestern Russia region.

The work on this project continues with further collection of waveforms for events of special interest, such as new events that have occurred /will occur in the study area, as well as some historical refraction shots undertaken

in the Baltic Sea and surrounding areas. The remaining work also includes the determination of bounds on seismicity in the Kara Sea.

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